Predictive Study on High Performance Modes of Operation in HL-2A[1]

Qingdi GAO 1), R. V. BUDNY 2), Fangzhu LI 1), Jinhua ZHANG 1), Hongpeng QU 1)

1) Southwestern Institute of Physics, Chengdu, Sichuan, P. R. China
2) Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA

e-mail contact of main author: qgao@swip.ac.cn

Abstract. High performance scenarios in the HL-2A tokamak are studied by numerical modeling. Through shifting the plasma column outwards a shaping plasma with significant triangularity is achieved with sufficient room left for the RF antenna. For the out-shifted shaping plasma, ripple loss of high energy ions during NBI is analyzed. The results show that the ripple loss fraction of NBI power for the shaping plasma is not higher than that for the unshifted circular plasma. The time dependent TRANSP code is used to model realistic reversed magnetic shear operation in HL-2A. In order to sustain the RS operation towards steady-state, off-axis current drive with a lower hybrid wave at 2.45GHz is used to control the current profile. A steady-state RS discharge is formed and sustained until the LH power is turned off; the plasma confinement is enhanced with the development of an internal transport barrier. In the RS discharges with shaping plasma geometry a double transport barrier is produced.

1. Introduction

The HL-2A tokamak [1], which is the first divertor tokamak in China, is under construction at SWIP, Chengdu, and will be ready for operation soon. The major objectives of HL-2A are to produce more adaptable divertor configurations to study energy exhaust and impurity control, and to enhance plasma confinement by profile control. A high density plasma, which is required for the cold and dense divertor, will degrade the plasma confine-ment. Recent experiments on JET, DIII-D, JT-60U and ASDEX [2-5] have shown the positive effects of triangularity on confinement. By using the flexible power supply system of the poloidal field coils in HL-2A, shaping plasmas with significant triangularity can be produced.

The studies [6,7] on the optimization of the current density profile suggest that reversed magnetic shear (RS) is desirable for confinement, stability and bootstrap alignment. In many tokamaks, RS plasmas develop an internal transport barrier (ITB) that produces improved central confinement. However, the RS discharges established in the early experiments were usually transient in nature due to the development of MHD instabilities. The experimental observation of greatly reduced transport in RS plasmas provides a strong motivation to further explore current profile control by which optimized RS operation may be established and maintained for timescales beyond the characteristic current diffusion time. In the HL-2A tokamak, the various schemes of auxiliary heating and current drive, including NBI (3MW), ICRH (1MW), LHCD (2.5MW), and ECRH (0.5MW), offer the opportunity to optimize the current profile.

2. Plasma Shaping

Though the divertor coils are fixed in the vacuum vessel in HL-2A, plasma shaping is possible through shifting the plasma column outwards. By reasonable adjustment of the currents in the vertical field coils and compensatory coils, shaping plasmas with significant triangularity have been achieved. The plasma equilibrium geometry is calculated with a free-boundary equilibrium code (SWEQU).Two typical shaping plasma geometries were produced:

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one is a D-shape plasma with R_0=1.76m, a=0.38m, δ_{95}=0.44, k_{95}=1.08 (Fig.1a); and another is an elongated D-shape plasma with R_0=1.74m, a=0.33m, δ_{95}=0.41, k_{95}=1.21 (Fig.1b). The triangularity variation with respect to the flux coordinate is dependent on the plasma current profile, but it decreases rapidly at the plasma boundary region for both hollow and peaked current profiles (Fig.2). The pressure of the H-mode pedestal, which is localized at the plasma edge, increases strongly with triangularity due to the increase in the margin by which the edge pressure gradient exceeds the ideal ballooning mode limit [3]; therefore, the rather high triangularity located at the plasma edge is favorable to enhancing the confinement.

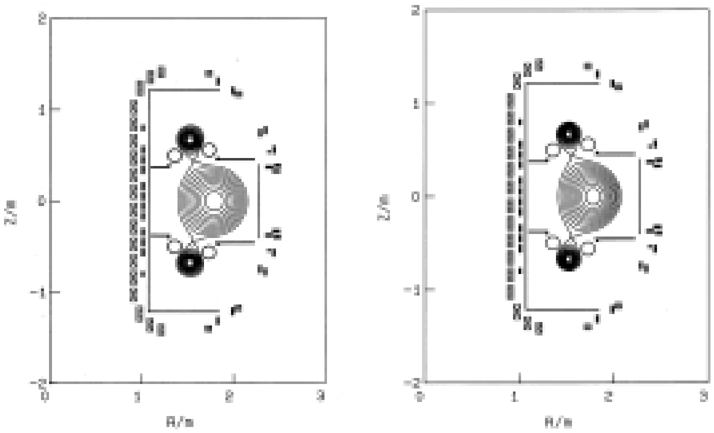

FIG.1. Magnetic geometries of the out-shifted plasmas; D-shaped plasma (left) and elongated D-shaped plasma (right)

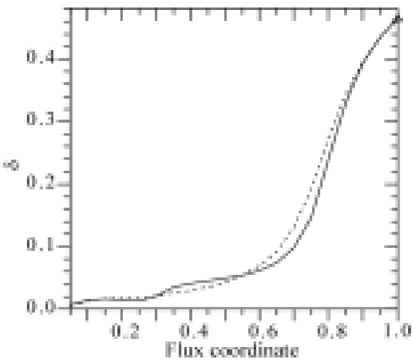

FIG.2. Triangularity δ versus the flux surface for the cases of hollow current profile (full line) and peaked current profile (dotted line).

For the out-shifted shaping plasma, ripple loss of high energy ions during neutral beam injection is estimated by assuming the trapped ions lost if their turning points are in regions where the ripple exceeds an empirical factor times the Goldston-White-Boozer threshold [8]. Ionization and capture of NBI particles, and slowing down of high energy ions are calculated with a Monte Carlo technique. The ripple loss, orbit loss, and charge-exchange loss are calculated separately. The toroidal field ripple $\varepsilon(R,Z) \equiv (B_{max}-B_{min})/(B_{max}+B_{min})$ generated by 16 D-shaped coils is calculated, showing that its value at the outer edge of the shifted plasma is rather high (close to 2%). The toroidal ripple contours are of elongated D-shape as shown in Fig.3, where the shift of the plasma position is shown as well. In order to show whether the ripple loss for the out-shifted plasma is tolerable we made a comparison for the ripple loss between shaping plasma and circular plasma. The results show that the ripple loss fraction of NBI power for the shaping plasma is not higher than that for circular plasma (Fig.4) because most high energy ions are not deeply trapped in the case of tangential neutral beam injection.

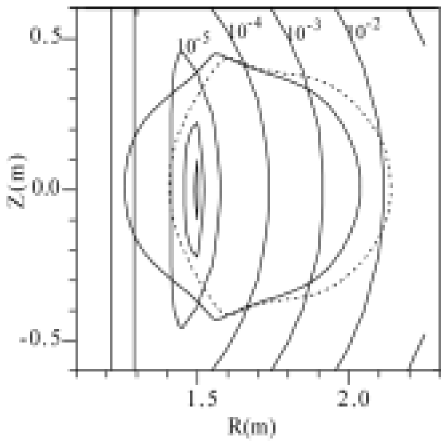

FIG.3. Contours of the toroidal field ripple. The locations of the circular plasma boundary (full line) and out-shifted plasma boundary (dotted line) are also shown.

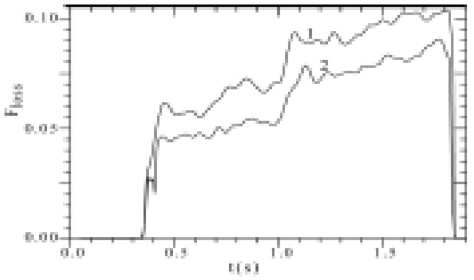

FIG.4. Ripple loss fraction of the NBI power, F_{loss}, vs. time for a circular plasma (curve 1) and an out-shifted plasma (curve 2).

3. Reversed Magnetic Shear Operation

Quasi-stationary RS discharges with ITB The time dependent TRANSP code is used to model realistic RS operation in HL-2A. In order to sustain the RS operation towards steady-state, off-axis current drive with a lower hybrid (LHCD) wave at 2.45GHz is used to control the current profile. The target plasma is maintained by means of 2.0MW neutral beam (1.5MW co-injection and 0.5MW counter-injection) injected into an Ohmic heating discharge of I_p=265kA with a modest peaking density profile ($n_e(0)/\langle n_e \rangle$=1.86, $\bar{n}_e = 2.31\times10^{19} m^{-3}$). The LHCD simulation and the plasma transport model have been described in Ref. 1. Due to the off-axis LHCD combined with the effect of bootstrap current and beam driven current a steady-state RS discharge is formed and sustained with the minimum q value, $q_{min} \approx 2.8$, and the location of q_{min}, $x_{min} \approx 0.65$, until the LH power is turned off (Fig.5). In the sustained RS discharge, plasma confinement is enhanced with the development of an ITB. The ITB manifests itself by the higher gradient of ion temperature inside it. It is maintained stationary during the whole RS phase, and the position of maximum $|\nabla T_i|$, where the minimum of ion heat diffusivity is located, is near x_{min}. When the reversed shear exists, the location of the ITB temporally evolves following the evolution of the shear reversal point (Fig.5b). The enhancement factor over ELMy H-mode as given by the IPB98(y,2) scaling is $H_{98(y,2)} \approx 1.1$, and the normalized β value is $\beta_N \approx 1.4$ (Fig. 5c).This RS discharge has achieved nearly a fully non-inductive current drive with a non-inductive current (which includes LH wave driven current, NBI driven current and bootstrap current) fraction of ~90% of the total plasma current and an LHCD efficiency $\eta_{CD} \approx 1.0\times10^{19} A/Wm^2$ (Fig.5d). The sustainable RS scenario is robust. We have performed the RS discharge modeling for various different target plasmas. In all these cases similar off-axis non-inductive driven current profiles as in the standard case are produced during the steady state phase, and quasi-stationary RS discharges are achieved.

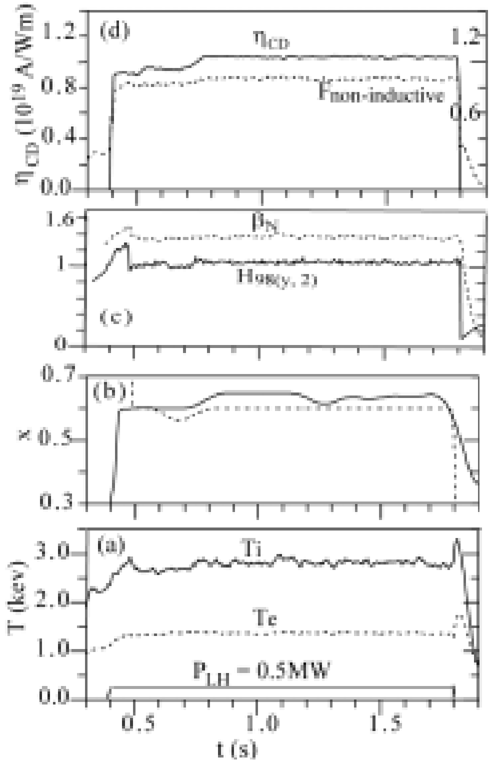

FIG.5. Temporal evolution of (a) the central plasma temperature, (b) the location of the minimum q (full line) and the minimum χ_i (dotted line), (c) the H-factor and normalized β, (d) LHCD efficiency and non-inductive current fraction.

RS discharge with double transport barrier The plasma boundary calculated in Sec.2 is used to model the RS discharge. The geometry of the boundary (98% flux surface of the diverted plasma) is specified as a general function of time. The interior flux surfaces, which are computed by solving the Grad-Shafranov equation, are parameterized by the square-root of the normalized toroidal flux, ρ. The standard target plasma set as above is used, and the current profile is still controlled by LHCD. A steady-state RS discharge is produced with a double transport barrier developed for the shaping plasma (δ_{98}=0.43, k_{98}=1.23). The double transport barrier is indicated by two abrupt decreases of the ion heat diffusivity (Fig.6), of which the two minimums are located near the shear reversal point, $\rho_{min} \approx 0.55$, and near the plasma edge, ρ ≈ 0.95, respectively. Taking into account the fact that the triangularity of plasmas improves the edge pressure limit as evidenced by many experiments [2-5], the transport barrier located near the edge will enhance the plasma confinement, such that higher plasma parameters (T_{e0} ~ 1.7keV, T_{i0} ~3.6keV, $H_{98(y,2)}$ = 1.17 – 1.34, β_N = 1.45 – 1.58) than those in Fig.5 are obtained during the stationary RS phase.

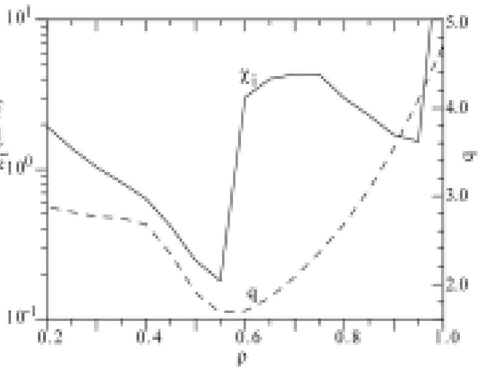

FIG.6. Profiles of q and ion heat diffusivity

LH wave deposition regime in the quasi-stationary RS plasma It turns out that in the modeled RS plasma the absorption of high phase velocity LH waves is too weak to ensure that the wave damped directly in the outer part of the plasma. The achievement of off-axis LH wave deposition would rely on wave propagation constrained by the LH wave dispersion relation and on multiple reflections in the plasma. The required condition for strong electron Landau damping (ELD) is

$$n_{//} = k_{//}c/\omega \geq 6.5/\sqrt{T_e[keV]} \qquad (1)$$

where $k_{//}$ is the wave vector component parallel to the magnetic field.

Under the conditions of the HL-2A RS discharges simulated above, there is a spectral gap between the parallel LHW phase velocity and the electron thermal velocity. To achieve off-axis LH wave power deposition in the weak damping regime, we rely on the $n_{//}$ upshift. Here, the $n_{//}$ upshift effect is estimated from the toroidal axisymmetry, yielding

$$n_{//} \leq n_{//0} \frac{R_0/R}{1-(\omega_{pe}/\omega)/(\hat{q}\varepsilon_\perp^{1/2})}, \qquad (2)$$

where $\varepsilon_\perp = 1+\omega_{pe}^2/\omega_{ce}^2 - \sum_j \omega_{pi,j}^2/\omega^2$, $\hat{q} = \frac{q_{cyl}}{\varepsilon x}$ ($\varepsilon = a/R$).

By solving the wave dispersion relation D(m, r, k_r, ω) = 0 for k_r on each flux surface for a given n, the region where the propagation is allowed (i.e. $k_r^2 \geq 0$) is defined. By using the cold electrostatic approximation, at the boundary of the propagation domain,

$$\bar{n}_{//} = n_{//0}\frac{R_0}{R}\frac{\hat{q}^2 \mp \sqrt{1+(1+\hat{q}^2)(\omega_{pe}^2/\omega^2)/\varepsilon_\perp}}{\hat{q}^2 - [1+(\omega_{pe}^2/\omega^2)/\varepsilon_\perp]} \qquad (3)$$

To show the off-axis LH wave power deposition in HL-2A, we draw the ELD limit, the $n_{//}$ upshift boundary, and the boundary of the wave propagation domain in the (x, $n_{//}$) plane (Fig.7). It is shown that the LH wave absorption is bounded in the region above the ELD limit and below the boundary of the wave propagation domain. For the quasi-stationary RS operation obtained with I_p=265kA, the spatial region of power deposition is limited to 0.5< x <0.8 (Fig. 7a), and it is off-axis. Nevertheless, when the plasma current increases to I_p=300kA, the RS will not be maintained. Under this condition the

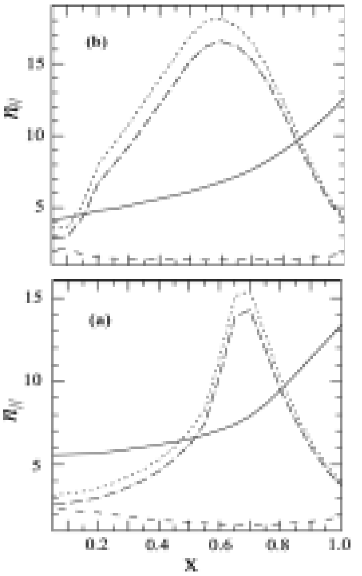

FIG.7. Regime of LH power absorption: ELD limit (full line); $n_{//}$ upshift boundary (dotted line); boundary of propagation domain (dashed line) (at t=1.0s). (a) I_p = 265kA, (b) I_p = 300kA.

intersection between the upper $n_{//}$ limit and the ELD limit is located at x ~ 0.15 (Fig.7b), and the LH power can deposit near the plasma center, which would increase the central electron temperature allowing the LH wave to penetrate further into the center, and the central peaking driven current is generated. It is concluded that the variation of the LH driven current profile is due to the constraint imposed by the wave propagation domain that can be controlled by changing the plasma parameters or the LH wave spectrum. By tuning the phasing between wave guides properly, a sustainable, although not so stationary as the discharges with I_p=265kA, RS discharge with I_p=320kA can be achieved, which is of higher $H_{98(y,2)}$ and β_N (Fig.8).

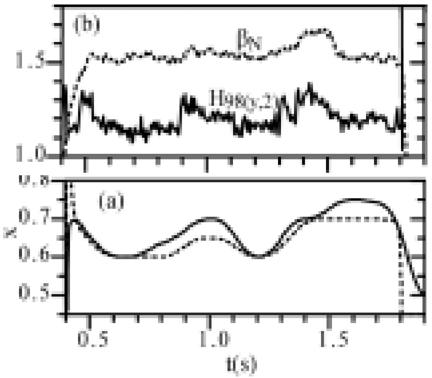

FIG.8. Temporal evolution of (a) the location of the shear reversal point (full line) and the minimum ion heat diffusivity (dashed line), and (b) β_N *and* $H_{98(y,2)}$.

4. Conclusions

Through shifting the plasma column outward, magnetic geometries with significant triangularity are achieved with sufficient room left for the RF antenna. For the out-shifted shaping plasma, ripple loss of high energy ions during neutral beam injection is analyzed. The results show that the ripple loss fraction of NBI power for the shaping plasma is not higher than that for the unshifted circular plasma.

The time dependent TRANSP code is used to model realistic reversed magnetic shear operation in HL-2A. In order to sustain the RS operation towards steady-state, off-axis current drive with a lower hybrid wave at 2.45GHz is used to control the current profile, and a steady-state RS discharge with an ITB is formed and sustained until the LH power is turned off. In the RS discharges with shaping plasma geometry, a double transport barrier is developed, and the transport barrier near the plasma edge combined with the effect of triangularity on raising the edge pressure gradient improve the plasma confinement.

As the initial parallel phase velocity of the LH wave is sufficiently high compared to the thermal electron velocity in the HL-2A plasma center, the wave absorption is weak and it makes many passes through the plasma until the initial launched wave spectrum is sufficiently broadened to be absorbed. Nevertheless, the constraint imposed by the wave propagation condition limits the maximum allowed $n_{//}$ upshift. Taking into account the Landau damping condition, an off-axis LH power deposition region is generated by choosing the plasma parameters properly, which points the way for current profile control with LHCD in establishing stationary RS operation.

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